ANALYSIS OF FOUNDATION SETTELEMENT ON FINE GRAINED SOIL (CLAYEY SOIL) IN BENIN CITY, EDO STATE, NIGERIA.

BY

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PLAGARISM

This work ANALYSIS OF FOUNDATION SETTLEMENT ON FINE GRAINED SOIL (CLAYEY SOIL) by Chukwuma Israel with Matriculation Number ENG2002107 of the Department of Civil Engineering, University of Benin City, Edo State. Nigeria, has PASSED the PLAGIARISM TEST.

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CERTIFICATION

This is to certify that this work was carried out by Chukwuma Israel, Matric No. ENG2002107, of the Department of Civil Engineering, Faculty of Engineering, University of Benin City, Edo State, Nigeria.

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DEDICATION

I dedicate this endeavor primarily to God, my family and my friends.

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ABSTRACT

The study was carried out to analyze the settlement behaviors of fine-grained soils-that is, clayey soils-in Benin City, Nigeria, with a view to understanding their geotechnical characteristics and compressibility under loads. Justification for this research lies in the frequent structural failures and foundation instabilities observed in clayey sub-soils across the region

Various soil samples collected from the University of Benin and environs were tested for their physical and engineering properties in the laboratory. Standard tests such as moisture content, specific gravity, particle size distribution, Atterberg limits, and consolidation, in line with ASTM and BS standards, were carried out to study soils' compressibility and settlement behaviors under applied loads.

The natural moisture content of the soils varied between 18.6% and 22.4%, while the average specific gravity was 2.57. In addition, the Atterberg limits gave a liquid limit of 38-42%, plastic limit of 22-23%, and plasticity index of 16-19%, classifying the soils as inorganic clays of low to medium plasticity CL under the USCS and A-7-6 under AASHTO. More than 50% of soil particles passed the 0.075 mm sieve, which confirms fine-grained, cohesive soils that are characteristic of the Benin Formation. The results of the consolidation (oedometer) test show that settlement increases with applied pressure between 12.5 kPa and 250 kPa, whereas the coefficient of volume compressibility, Mv, decreases from 0.1× 10^{-3} and 1.0× 10^{-3} m^2 /kN, indicating moderate to high compressibility. Generally, these soils are characterized by moderate plasticity, low permeability, and high settlement potential; hence, foundation designs should consider soil stabilization, preloading, or raft and pile foundations, with adequate drainage control to ensure long-term stability.

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ACRONYMS

LL - Liquid Limit

PL - Plastic Limit,

PI - Plasticity Index

OMC - Optimum Moisture Content,

MDD - Maximum Dry Density,

UCS - Unconfined Compressive Strength

ASTM - American Society for Testing and Materials

BS - British Standard, such as BS 1377

CPT - Cone Penetration Test

PLT - Plate Load Test,

SPT - Standard Penetration Test,

SSI - Soil-Structure Interaction

FEM - Finite Element Method,

AASHTO - American Association of State Highway and Transportation Officials

Mv - Coefficient of Volume Compressibility

Gs - Specific Gravity of Soil Solids

kPa - Kilopascal (unit of pressure)

CL - Inorganic Clay of Low to Medium Plasticity (USCS Classification)

A-7-6 - Clayey Soil Group under AASHTO Classification

UBN - University of Benin Nigeria

EKS - Ekosodin

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The performance and safety of civil engineering structures such as buildings, roads, and bridges are significantly dependent on the ground conditions on which they are founded. Fine-grained soils, which are predominantly clays, pose unique geotechnical issues due to their high plasticity, low permeability, and susceptibility to water content. These properties make them highly susceptible to volume change, which is often the source of problematic foundation settlement (Abbey, and Utsav, 2019). Foundation settlement, or downward movement of structure due to deformation or consolidation of soil underlying the structure, is particularly important in fine-grained soils and can lead to building tilting, cracking, or collapse.

Fine-grained soils exhibit nonlinear stress-strain response under unsaturated conditions governed by matric suction and water content. Recent work by Oh and Vanapalli (2016) has demonstrated how Poisson's ratio a soil parameter that defines the elastic response of the soil—can significantly vary in unsaturated clay soils. This variation affects not just deformation characteristics but also stress distribution under shallow foundations. The standard assumption of a constant Poisson's ratio underpredicts settlement in design models. Thus, application of more realistic, moisture-dependent parameters in settlement prediction is necessary.

Apart from physical and mechanical properties, fine-grained soils also show pronounced regional variability. Compressible and expansive clay soils are widespread in most of Nigeria, e.g., the Middle Belt and southern states. Damage to infrastructure facilities due to foundation instability is extremely common in these regions. For example, excessive settlement on clay soil has been witnessed in cities like Benin City, Ibadan, and parts of Abuja, where site investigation malpractice, poor drainage, and high rainfall intensiveness have led to frequent foundation failure (Eze-Uzomaka, *et al*, 2019).

The use of empirical and numerical approaches to predict settlement behavior has gained increased popularity over the years. Scholars such as Salih *et al*. (2022) have employed the finite element analysis (FEA) using programs such as PLAXIS 3D in the simulation of the load-settlement response of shallow foundations on clay. The simulations provide insight into the influence of different parameters soil modulus, change in water table depth, and loading conditions on the stability of the foundation. However, their accuracy depends heavily on having good-quality soil input data, which is typically lacking or heterogeneous in developing nations.

Additionally, artificial intelligence and machine learning-based new methods for predicting consolidation and settlement behavior have been introduced. For instance, Mohammadzadeh *et al*. (2019) proposed gene expression programming for estimating the compression index of fine-grained soils—one of the most significant consolidation analysis parameters. In spite of quicker and perhaps more accurate predictions from such models, their practical application has been minimal so far due to the need for high-quality datasets and special expertise.

Despite global progress in fine-grained soil settlement behavior understanding and modeling, studies in Nigeria are scarce and fragmented. Most building failures in clay-dominated regions are still due to poor site characterization, insufficient geotechnical testing, and simplification of foundation design practice. Neither is there consideration of post-construction monitoring that would be necessary to verify design assumptions and determine long-term foundation performance.

It is against this background that the present research is set to conduct a detailed examination of foundation settlement in fine-grained soil, focusing specifically on the behavior of clay soil under different load and moisture conditions. The study will involve laboratory testing of soil samples, simulation of loading conditions, and application of predictive models in analyzing the settlement behavior. It is directed towards developing reliable, locally applicable knowledge of foundation behavior on clay soil that can translate into more sustainable structural design in regions of similar geotechnical profiles.

1.2 Statement of the Problem

The classic issue of foundation settlement on fine-grained (clay) soils remains a basic issue in geotechnical and structural engineering practice, particularly in regions with naturally weak or moisture-sensitive subsoils. Despite significant advances in understanding the behavior of soils under load, structural damage associated with foundations continues to occur principally due to inadequate site investigation, over-simplistic soil modeling, and a general underestimation of time-dependent settlement behavior in cohesive soils (Bahmani and Briand, 2021).

Clay soils, unlike sandy soils, possess low permeability and high compressibility. These characteristics induce delayed consolidation and excess settlement under variable or sustained loading after construction. Foundations supported on these soils are very prone to differential settlement—non-uniform ground movement that leads to wall cracking, frame distortion, and even partial collapse of structures (Abbey and Utsav 2019). Yet, for most developing regions including Nigeria's portion designers rely on general assumptions or small-scale laboratory tests that cannot capture real behavior of local clays (Ukeme, 2025).

In regions such as Benin City, Edo State, rapid urbanization has increased the need for low- to medium-rise commercial and residential buildings. Soils herein, although traditionally described as reddish-brown silty clays, display textbook features of fine-grained problem soils, including medium to high plasticity, unpredictable shear strength, and moisture-sensitive volume change behavior (Eze-Uzomaka, *et al* 2019). Despite these extensively reported challenges, site-specific foundation performance records remain limited, and the majority of developments proceed with a lack of proper geotechnical investigation. This ignorance at the local level is largely responsible for the increasing trend of premature structural distress, manifested in the form of foundation cracking and settlement failure in the majority of the neighborhoods in the city (Ukeme, 2025).

In addition, the fluctuation in moisture content due to seasonal rainfalls, inadequate drainage, or unprofessional landscaping practices alters the effective stress in clay soils and results in swelling or shrinkage. These changes produce complex stress-strain behavior in the soil, particularly in the unsaturated zone a response not easily predicted by the application of conventional settlement equations (Oh and Vanapalli, 2016). The conventional methods widely used to predict settlement in clayey soils, therefore, may not provide good predictions under field conditions.

Missing from the current knowledge base is a detailed, context-specific understanding of how the clay soils will perform under foundation loads in Benin City's geologic and climatic environment. Empirical correlations and models available developed primarily in temperate nations may be inadequate to capture local soil mineralogy, rainfall intensities, or urban development patterns common in tropical environments like southern Nigeria.

By focusing on the behavior of fine-grained soil at real site and environmental conditions, the research seeks to contribute towards safer, more durable foundation designs, and towards reducing the financial costs of building distress and collapse in clay-rich regions of Nigeria.

1.3 Aim and Objectives of the Study

The Aim of this project is to carry out analysis of foundation settlement on fine-grained soil (clayey soil). The objectives are:

1)To analyze the geotechnical properties (e.g., plasticity index and moisture content) of fine-grained soils collected from selected sites in Benin City, Edo State, Nigeria.

2)To analyze the settlement behavior of shallow foundations on clayey soil via laboratory simulation.

1.4 Scope of the Study

This work is devoted to the study of the behavior of foundation settlement in general in fine-grained soil and specifically in clayey soil. The research is concerned with shallow foundations such as pad, strip, and raft foundations, which are typically affected by the characteristics of the underlying clayey layers.

The research involves theoretical and experimental investigation on the behavior of clay soil under loading with a focus on immediate, primary consolidation, and secondary settlement mechanisms. The laboratory experiments like moisture content determination, Atterberg limits, compaction test, and one-dimensional consolidation test (oedometer test) will be considered in determining the engineering properties of clay soils and evaluating their settlement potential.

The study further explores analytical methods, including Terzaghi’s one-dimensional consolidation theory, to estimate and assess settlement.

Geographically, this study will be confined to Benin city as the sample location with known clayey subsoil conditions.

1.5 Justification of the Study

The relevance of this study is the wide prevalence and problematic nature of clay soils in the majority of construction sites worldwide. The fine-grained soils, clays especially, possess high compressibility, low shear strength, and low drainage abilities that make them experience large and often unpredictable settlement beneath structural loads. Unless these soils are not explored or provided for in design, foundation settlement will cause costly damage, structural instability, and even collapse.

Both in the developing and developed world, increasing urbanization and infrastructural development have pushed engineers to build on marginal soils, including clays. Proper understanding of the behavior of clayey soils beneath foundation loads is therefore not only of academic but practical interest for the sake of safe and durable construction. Inadequate consideration of settlement behavior has had catastrophic consequences, including cracked walls and floors, tilting buildings, and loss of serviceability in buildings and highways.

Besides, the majority of the previous studies have been oriented towards general soil behavior with no specialization in the particular problems of clayey soils. The current project is a specialized study which is oriented towards the particular settlement behavior of clays, commonly governed by their high water-holding capacity and slow consolidation reaction. Through laboratory test, theoretical analysis, and case study, the current study tries to fill crucial knowledge gaps and to provide engineering solutions for use on real projects.

The project output will be a practical manual for building practitioners, geotechnical consultants, and civil engineers who are often confronted with the issue of foundation design on clay soils. It will also enlighten policy makers, developers, and academic researchers in coming up with best practices in construction over problematic soils.

CHAPTER TWO

LITERATURE REVIEW

2.1 Concept of Foundation Settlement

2.1.1 Definition and Types of Settlement

Foundation settlement is the settlement or subsidence of a structure as a result of deformation or compressing the ground under working loads. It's an important geotechnical parameter that affects structural stability and operation ability. Three kinds of settlement are classified:

1. Elastic (Immediate) Settlement: Immediate on loading as a result of elastic deformation of soil, but big in coarse-grained soils and also in clays for high-speed loading (Terzaghi *et al*., 1996).
2. Primary Consolidation Settlement: A time-dependent process, whereby water is expelled from pore spaces of clays carrying permanent loads, occurring in the majority of Nigerian coastal clays (Lambe and Whitman, 2000).
3. Secondary Compression (Creep) Settlement: Occurs after primary consolidation as a result of particle rearrangement under conditions of constant stress, typical of Niger Delta organic clays (Mesri and Godlewski, 1977).

2.1.2 Reasons for Settlement

Settlement of clay soil is controlled by:

i. Soil Type and Characteristics: Plasticity and compressibility of clays such as Bayelsa State's montmorillonite soils render settlement very significant. For instance, Benin City's lateritic clays with high plasticity indices that improve settlement potential (Oyediran and Iroezindu, 2013).

ii. Magnitude and Duration of Load: Heavy, long-lasting loads, i.e., that of multi-story buildings in Lagos, cause an increase in primary consolidation. Settlement was enhanced under constant industrial loads in a study of Port Harcourt (Osinubi and Charles, 2010).

iii. Groundwater Conditions: Nigeria's seasonal rain is responsible for the variation of groundwater levels, which results in swelling and shrinkage in expansive clays. Monsoon-swelling resulted in differential settlement of dwellings constructed on clay soils in Lagos. (Ikuemonisan *et al.* 2021).

2.1.3 Settlement Implications

Excessive settlement results in:

a. Damage to Structure: Foundation and wall cracking, observed in low-rise buildings in Benin City (Ejezie, 2012).

b. Serviceability Issues: Warped floors and improperly aligned doors, such as in the situation of Bayelsa's public buildings (Abor and Sule, 2012).

c. Financial Consequences: Costs for repairs, time overruns, and structural failure exemplified by multiple Lagos estates continue to incur massive expenditures due to foundation and subsidence issues (Ohenhen and Shirzaei, 2022).

2.2 Characteristics of Fine-Grained Soils (Clay Soils)

2.2.1 Mineral Content

Clay minerals like montmorillonite, kaolinite, and illite soils. Montmorillonite, which is common in Niger Delta of Nigeria, is highly expansive because of water uptake and swelling to change the volume. Lateritic soil kaolinite is less expansive and illite has moderate plasticity (Oyediran and Okosun, 2013; Osinubi and Charles, 2010).

2.2.2 Physical Properties

Key properties are:

i. Plasticity Index (PI): High PI of Nigerian clays (e.g., PI > 30 in Bayelsa) indicates high potential for swelling (Ikuemonisan *et al.*, 2021).

ii. Liquidity Index (LI): High LI of Benin City clays indicate susceptibility to load deformation (Oyediran and Iroezindu, 2013).

iii. Shrinkage Limit (SL): High linear shrinkage values (11–18%) observed in expansive clays from southeastern Nigeria confirm significant shrink–swell behavior and resultant cracking during dry conditions (Chukwu and Eze, 2019).

2.2.3 Engineering Behavior

The clayey soils possess:

a. Compressibility: Excess compressibility in Bayelsa organic clays leads to greater settlements, for example, during the construction of Yenagoa hospital where settlement of 150 mm was observed (Osinubi and Charles, 2010).

b. Permeability: Low permeability in Lagos clays slows down dissipation of pore water, slowing consolidation (Adeyeri *et al.*, 2017).

c. Shear Strength: Low shear strength in Benin City clays caused bearing capacity failure in shallow foundations (Ohenhen and Shirzaei, 2022).

d. Swelling and Shrinkage: In Bayelsa, seasonal swelling of montmorillonite-rich clays caused differential settlement in a school building, necessitating pile foundations (Abor and Sule, 2012).

2.3 Theories on Settlement Prediction

2.3.1 Terzaghi's One-Dimensional Consolidation Theory

Terzaghi's theory predicts settlement in saturated clays, assuming one-dimensional water flow. Its limitations include assuming linear soil behavior, less applicable to Nigeria's non-linear clays (Terzaghi *et al.*, 1996).

2.3.2 Developments in Consolidation Theories

Three-dimensional and non-linear modeling, for example, finite element approaches (FEM) within PLAXIS, can handle soil heterogeneity. FEM modeled settlement in a Nigerian refinery in Port Harcourt, which was non-linear for high-plasticity clays (Osinubi and Charles, 2010; Oyediran and Okosun, 2013).

2.4 Foundation Settlement Assessment Techniques

2.4.1 Laboratory Techniques

i. Oedometer Test: Lays down consolidation parameters. Testing is limited in Nigeria by inadequate oedometer facilities; an imported equipment was used in Benin City research, incurring increased costs (Adeyeri *et al.*, 2017).

ii. Unconfined Compressive Strength (UCS) Test: Varies shear strength. UCS was used by a Lagos project to confirm low strength in marine clays with design implications on piles (Osinubi and Charles, 2010).
iii. Atterberg Limits: Tests plasticity. High liquid limits of Bayelsa clays (LL > 60%) indicate high risk of settlement (Ikuemonisan *et al*, 2021).

2.4.2 Field Testing Methods

1. Plate Load Test (PLT): Tests for immediate settlement. PLT in Benin City indicated excessive settlement in shallow foundations, and therefore raft foundation use ensued (Ejezie, 2012).
2. Cone Penetration Test (CPT): Provides soil profiles. Unavailability of CPT equipment in Nigeria necessitates greater reliance on SPT; CPT was used by a Lagos project to identify clay layers (Abor and Sule, 2012).
3. Standard Penetration Test (SPT): Provides estimates of soil strength. Widely used in Benin City due to the fact that it is cheap, though not as reliable for soft clays (Oyediran and Iroezindu, 2013).

2.4.3 Numerical Modeling

i. Finite Element Analysis (FEA): Resolves intricate loading. PLAXIS modeled settlement of a Bayelsa bridge plan, predicting 200 mm consolidation (Osinubi and Charles, 2010).
ii. Software Application: GeoStudio groundwater model aided settlement prediction in saturated clays of Lagos, which is critical for high-rise buildings (Adeyeri *et al.*, 2017).

2.5 Soil-Structure Interaction in Clayey Soils

2.5.1 Definition and Importance

Soil-structure interaction (SSI) is the interaction of supporting soil and a structure, significant in clays due to low stiffness and high compressibility causing differential settlements (Ejezie, 2012).

2.5.2 Soil-Structure Interaction (SSI) factors

a. Soil Stiffness: Overly excessive settlement at a Yenagoa market that required deep foundations resulted from low stiffness of Bayelsa clays (Osinubi and Charles, 2010).
b. Type of Foundation: Benin City clay shallow foundations experienced 100 mm differential settlement, as compared to pile foundations (Abor and Sule, 2012).
c. Conditions of Load: Cyclic traffic load in Lagos intensified settlement in Lagos Road pavement clayey soils (Oyediran and Okosun, 2013).

2.5.3 Model Approaches

i. Analysis Techniques: Winkler's approach, used in earlier Nigerian designs, simplifies the behavior of clay and results in erroneous predictions (Ohenhen and Shirzaei, 2022).
ii. Numerical Modeling: PLAXIS FEM simulated SSI in Port Harcourt tower, with measurements of non-linear clay behavior (Osinubi and Charles, 2010).

2.6 Foundation Design Techniques in Problematic Soils

2.6.1 Shallow and Deep Foundations

a. Shallow Foundations: Suitable for foundation of low-rise buildings in moderately compressible clays, such as Benin City residential estates, but require settlement minimization (Ejezie, 2012).
b. Deep Foundations: Bayelsa soft clays are over-loaded with piles to hard layers, e.g., in a Yenagoa hospital (Abor and Sule, 2012).

2.6.2 Soil Improvement Techniques

i. Preloading: Used for Lagos' Eko Atlantic project for preloading-induced settlement before construction (Oyediran and Iroezindu, 2013).
ii. Vertical Drains: Fast consolidation in Bayelsa saturated clays to build roads (Adeyeri *et al.*, 2017).
iii. Chemical Stabilization: Lime stabilization in Benin City stabilized plasticity of clay for a school foundation (Osinubi and Charles, 2010).

2.6.3 Design Codes and Guidelines

1. Eurocode 7: Guides soil testing but is not supplemented with special provisions for Nigeria expansive clays. A Lagos project adapted Eurocode 7, requiring local soil data calibration (Ohenhen & Shirzaei, 2022).
2. Nigerian Standards: NCP 4:2005 provides general guidelines but is not supplemented with extensive expansive clay procedures, hence limiting its application in Bayelsa (Ade, 2005).

2.7 Summarization of Literature Review

The literature underscores that foundation settlement in clayey soils is complex, driven by soil properties, loading, and groundwater. Nigerian clays, with high plasticity and expansiveness, pose challenges in regions like Benin City and Bayelsa. Theories like Terzaghi's and Biot's, enhanced by numerical modeling, improve prediction accuracy. Laboratory and field tests, despite equipment limitations, are vital, as is SSI modeling. Foundation construction and ground improvement are critical in mitigation. Research and code uptake deficits exist in local studies, which this study aims to address.

2.8 Worldwide and Local Foundation Settlement Studies

2.8.1 Global Case Studies

i. Netherlands: Preloading and vertical drains, in which settlement in soft clays is encompassed, can be used in Nigeria's Niger Delta (Van der Meer *et al*., 2019).
ii. China: Deep foundations are used by Shanghai skyscrapers to resist settlement of clays, which can be applicable to city schemes in Lagos (Chen *et al*., 2015).

2.8.2 Nigerian Context

a. Benin City: PI > 25 lateritic clays caused settlement of 120 mm at a school, resisted by preloading and raft foundations (Oyediran and Iroezindu, 2013).
b. Bayelsa State: Yenagoa organic clays, LL > 70%, caused 200 mm settlement in a market, which was corrected by piles (Abor and Sule, 2012).
c. Lagos: Marine clays under a residential estate caused differential settlement, and chemical stabilization was needed (Ejezie, 2012).

d. Problems: Shallow testing facilities, empirical approach, and code non-compliance cause settlement prediction to be difficult, such as in Port Harcourt's industrial growth (Adeyeri *et al*., 2017).

2.9 Empirical Framework

Several empirical studies have tried to understand and estimate the settlement behavior of foundations on fine-grained (clayey) soils under various geotechnical conditions. One of them, a study by Lei *et al*. (2024), introduces a rate-dependent viscoplastic model for long-term tunnel settlement in clayey soil. Through FLAC3D simulations and multi-year field observations, they report settlement stabilizes at about 0.0015 mm/day and stress the role of viscoplasticity and time-dependent deformation in design. A Northern Iraqi case study that employs Plaxis 3D simulations to model raft foundation behavior shows that foundation width increases significantly reduce settlement, with thickness having a secondary effect (Hamid *et al*., 2022). This validates the role of plan dimensions in shallow foundation optimization.

An article proposes a CPT-based nonlinear settlement prediction method. Their method adapts dynamically to local site soil conditions and gives better predictive accuracy than traditional methods (Fatemeh and Abolfazl, 2019). An article proposes a layer wise summation method on the basis of the Duncan-Chang model. It provides better reliability in nonlinear deformation simulation and layer-by-layer vertical stress contribution division for total settlement calculation (Zhang Chao, 2012). A paper distinguishes the immediate and consolidation settlement of saturated clays and presents a practical model improving agreement with observed field performance, providing fundamental insight still used in designs today (Skempton and Bjerrum, 1957).

A paper utilizes Monte Carlo simulation with a stochastic elastic modulus field to illustrate that the total settlement is log-normally distributed and the differential settlement is exponential, enhancing probabilistic foundation design procedures (Fenton *et al*., 1995). A paper provides stochastic FEM analysis of immediate settlement in anisotropic soil layers. They emphasize that both anisotropy and fluctuation scale significantly affect settlement predictions and advise caution in assuming homogeneous soil (Jamshidi *et al*., 2019). Random field theory and a Monte Carlo analysis are applied in one study to soft soils. They illustrate that spatial variability, particularly in modulus and cohesion, has a significant effect on predicted settlements and warrants the application of probabilistic models (Lin *et al*., 2018). A paper emphasizes the inclusion of equal settlement design. It is reported to reduce structural stress concentrations and durability of structures on soft clays (Tulakov, *et al*, 2024).

A paper proposes a correction factor for estimating initial settlement from FEM-based plots. Their method reduces the necessity for full-scale laboratory testing and is best used where the ratios of shear stress are low (D'Appolonia *et al*., 1971). Research assesses the effect of deep soil mixing on Iranian clayey soils and determines that the addition of more cement content enhances strength and decreases settlement considerably. Their research corroborates DSM as an efficient soft clay mitigation method (Alipour *et al*., 2017). Research utilizes full-scale pile load tests to investigate settlement behavior. They note that longer piles subjected to high loading undergo settlements of up to 85 mm, and highlight the fact that pile length plays a significant role in serviceability in regions like Hong Kong (Zhang and Xu, 2004). CPT response in fine-grained soils with drainage changes is handled in one paper. Their finite element studies provide theoretical backbone curves enabling stiffness and strength to be more accurately predicted from CPT records (Tatiana *et al*., 2024).

A study provides an overview of the soil–structure interaction under dynamic loading using the Boundary Element Method. He discusses seismic safety in foundation systems and nonlinear soil behavior under vibrations (Cakmak, 1986). A study compares geosynthetic and pile foundation performance under seismic loading. Using the example of Taiwan's earthquake status, they illustrate that geosynthetic inclusion reduces settlement under dynamic stress (Mahdi *et al*., 2018). A paper derives a model for embedded foundations on elastic soil that reduces settlement prediction by transforming embedded foundations into equivalent surface footings. Their reduction technique, based on analysis, factors in embedment depth and edge effects (Guoxiong and Meijuan, 2013). A paper expounds on full-scale embankments using cam-clay theory. They demonstrate the decrease of settlement and lateral deformation of marine clays by sand compaction piles and vertical drains (Buddhima *et al*., 1997). One study analyzes plastic settlement of non-ballasted slab railroad tracks on fine-grained soils. He confirms that plastic deformation can be minimized by improved subgrade preparation and design stiffness (Jiunn-Shyang Chiou, 2019). Non-homogeneous granular piles in clayey soils were researched and it was established that settlement behavior is highly sensitive to the gradation of the material and pile-soil interface, once more reaffirming the necessity of site-specific designs (Pooja and Jitendra, 2018). A study compares piled raft foundation performance using Plaxis and ANSYS. They observe that as pile spacing increases, the load on piles reduces by over 20%, influencing settlement as well as design optimization (Hussein *et al*., 2021).

There are various studies on the control and prediction of foundation settlement, especially for fine-grained (clayey) soils. A China case study of immersed tunnels on clayey soils developed a rate-dependent viscoplastic model and concluded that long-term settlement stabilizes at about 0.0015 mm/day, emphasizing the importance of time-dependent behavior for clayey foundations (Kou *et al.*, 2024). A 3D Plaxis simulation study in Iraq reached the conclusion that settlement is significantly reduced through the process of raft foundation widening, illustrating the contribution of foundation geometry to deformation control on soft clay (Hamid *et al.*, 2022).

A CPT-based nonlinear method settlement study illustrated that stress–strain relationships calibrated against local soil conditions provided more accurate predictions than traditional elastic methods (Valikhah and Eslami, 2019). In Nigeria, a study utilized empirical correlations and elastic models in settlement prediction of raft footings on shale formations. It found that there was insignificant effect of raft thickness on settlement, while other parameters, like embedment depth, have more influence (Bunyamin and Aghayan, 2017). In Iran a study tested deep soil mixing with cement in clayey soils and concluded that there is a significant settlement reduction with the higher cement content, as an effective ground improvement technique in poor ground (Alipour *et al.*, 2017).

A study conducted full-scale pile load tests and concluded that foundation settlement is affected considerably by pile length, particularly in deep soft soils like Hong Kong soils (Zhang and Xu, 2004). One study used probabilistic analyses in Southern China to show that settlement prediction is greatly affected by uncertainty in soil parameters like cohesion and elastic modulus, warranting the use of spatial variability models in design (Huang *et al.*, 2018). One study simulated instantaneous and consolidation deformation using FEM and Biot theory, showing better settlement prediction when both time-dependent and elastic responses are considered (Shao *et al.*, 2011). One study illustrated that foundation failure is generally a consequence of designs that are just based on bearing capacity with no settlement consideration, showing the need for uniform settlement design criteria (Tulakov and Mamatkulova, 2024).

One study differentiated between immediate and consolidation settlement and proposed a model that was in closer agreement with field data than conventional methods. The model showed the role of clay characteristics in settlement (Skempton and Bjerrum, 1957). It is one research that used Monte Carlo simulation and concluded that the overall settlement is log-normally distributed, while differential settlement is better described using an exponential distribution, making it easier to apply reliability-based design procedures (Fenton *et al.*, 1995). Stochastic FEM was used for anisotropic soils in one research and concluded that anisotropy of the soil stiffness has a significant influence in raising the settlement values predicted (Jamshidi *et al.*, 2019).

A paper provided correction factors through FEM plots to predict initial settlements and showed that shear stress ratio is a very important parameter in predicting early deformation on clay foundations (D'Appolonia *et al.*, 1971). A paper provided a basic overview of consolidation theory and pointed out the need for empirical data as well as solutions because of partially saturated soils common in tropical countries like Nigeria (Seed, 1965). One paper proposed a Monte Carlo model for simulating settlement variation of floating foundations in soft clay and showed that ignoring variation can lead to unsafe or overly conservative design (Suk Nam Kim, 2002). One paper employed the elastic-visco-plastic (EVP) model and showed that it better captured time-dependent settlement behavior of the soft soil in BinHai Garden than classical plasticity models (Guo *et al.*, 2018).

A study developed a simple analytical model that transforms embedded foundations to equivalent surface footings in good agreement with field measurement and less need for complicated numerical simulation (Mei and Xu, 2013). A study compared pile and geosynthetic foundations under seismic loading and found that geosynthetics more effectively minimized settlement under dynamic load in clayey soil conditions (e.g., Taiwan earthquake) (Mahdi *et al*., 2018). There was a study conducted on granular piles in clay and concluded that material gradation and pile stiffness variability contribute significantly to settlement performance, with the conclusion of the necessity of improvement measures that are customized (Pooja and Sharma, 2018).

There was a study that employed Plaxis and ANSYS in simulating piled raft systems and concluded that pile contribution to load is minimized by increasing pile spacing, thereby influencing settlement behavior. They recommend enhanced pile groups in clay soils (Karim *et al*., 2021). A comparison indicated that the EVP model is superior to conventional viscoplasticity models in predicting the long-term settlement behavior of soft soil. Their work validates the adoption of advanced rheological models in compressible soils (Jing *et al*., 2018). A study proposed a granular compaction pile settlement method considering pile interaction and lateral deformation with more experiment-near predictions compared to conventional older methods (Hwang Jung-Soon *et al*., 2004). A study hybridized Least Squares Support Vector Machines (LS-SVM) with Monte Carlo simulations to show that flexible foundations undergo more settlement variability compared to rigid foundations. Their suggested machine learning-based solution provides a high-accuracy solution (Nazarzadeh and Sarbisheh, 2020). A study utilized FEM and empirical models in modeling raft footing on shale in South-East Nigeria and affirmed that empirical formulas like Steinbrenner's compared well with Plaxis 3D predictions, which was helpful under data-poor circumstances (Anigilaje and Aghayan, 2017). Another study highlighted that the existence of a rigid crust layer alters foundation deformation modes supported by stone columns. They found that traditional analysis models can underestimate settlement when such crusts are present (Athina *et al.*, 2019).

CHAPTER THREE

METHODOLOGY

3.1 Study Area

3.1.1 Geographic Location

This study was carried out using soil samples that were collected from selected construction sites within Benin City, the capital of Edo State, Nigeria. Geographically, Benin City is located between latitudes 6.20°N and 6.37°N and longitudes 5.37°E and 5.65°E, covering an estimated area of about 1,204 km².

The city lies on a gently undulating lowland with an average elevation of approximately 91 meters above sea level. The area is drained by rivers such as the Ikpoba, Ogba, and Osse, which influence the groundwater table and subsoil moisture conditions. The underlying geology consists predominantly of the Benin Formation, made up of sandy sediments interbedded with fine-grained clay layers. These clayey soils were of particular interest in this study because of their low permeability and high compressibility, properties that make them susceptible to settlement under structural loads.

Benin City experiences a tropical monsoon climate, with annual rainfall ranging between 1,500 mm and 2,500 mm, high relative humidity, and alternating wet and dry seasons. These climatic variations were observed to significantly influence the moisture content and consolidation behavior of the clayey soils investigated.

Due to rapid urban development, the native vegetation cover has been considerably modified, although fine-grained clay soils remain prevalent at the selected sampling sites.

These conditions made the study area suitable for analyzing the settlement behavior of shallow foundations on clayey soils through controlled laboratory tests and analytical modeling. The map of the study area is shown in figure 3.1

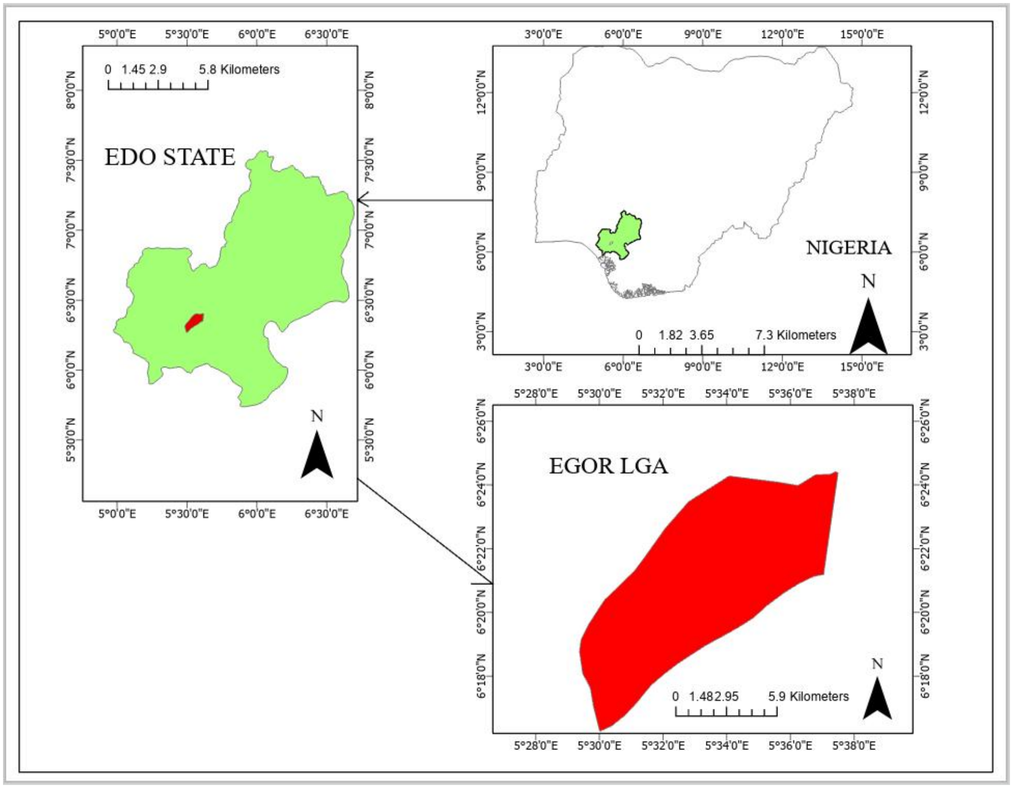

Figure 3.1 – Map of Study Area

3.1.2 Geology and Soil Profile

The study area was situated within the geologic framework of the Benin Formation, a component of the Niger Delta sedimentary basin. This formation was characterized predominantly by unconsolidated coastal plain sands and weathered lateritic profiles. These lateritic soils, which developed under tropical climatic conditions through intense weathering of underlying sedimentary rocks, were widespread across southern Nigeria, including Benin City. The upper soil layers were largely composed of laterite, underlain by fine-grained clayey subsoils, which were often encountered during foundation excavations.

Geotechnically, these soils were known to possess varied plasticity and were heavily influenced by seasonal changes in moisture. Lateritic soils in the area typically fell under A-7-5 and A-7-6 classifications in the AASHTO system and CL to CH in the Unified Soil Classification System (USCS), depending on their mineral composition and degree of weathering (Adeyemi and Afolagboye, 2015; Oluyinka and Olubunmi, 2018). These classifications indicated a predominance of low- to high-plasticity clays with significant silt content.

The plasticity index (PI) of soils from the region generally ranged between 8% and 22%, with liquid limits (LL) reported as high as 49%, depending on depth and location. These values suggested medium to high plasticity and potential for volumetric changes due to moisture fluctuations (Adunoye *et al.*, 2018). During the rainy season, the soils absorbed significant moisture, resulting in reduced shear strength and bearing capacity. In the dry season, shrinkage and desiccation cracking were common, posing risks of differential settlement for shallow foundations.

In terms of permeability, the lateritic and clayey soils demonstrated low permeability values in the order of 10^{-7} m/s, contributing to slow drainage and the buildup of excess pore water pressure under loading (Duruojinnaka *et al.*, 2016). This behavior was typical of fine-grained soils and played a major role in primary and secondary consolidation settlement, which could be particularly problematic for structures with long service lives.

Bearing capacity studies showed variability depending on compaction and stabilization methods. Some natural lateritic soils in southwestern Nigeria had low California Bearing Ratio (CBR) values (as low as 2–5%), requiring stabilization. However, when treated with additives such as cement or wood ash, these soils demonstrated substantial improvements, achieving CBR values exceeding 30% and meeting minimum requirements for foundation subgrade applications (Dabou *et al*., 2021).

The foundation settlement behavior in this region was therefore closely tied to the geotechnical properties of the underlying clayey soils. Without adequate treatment or design consideration, issues such as long-term consolidation, differential settlement, and bearing failure could occur. Consequently, for any engineering construction within this geological setting, there was a need for detailed subsurface investigation, appropriate foundation design, and possible soil stabilization measures. The soil classification map of Benin City is shown in figure 3.2

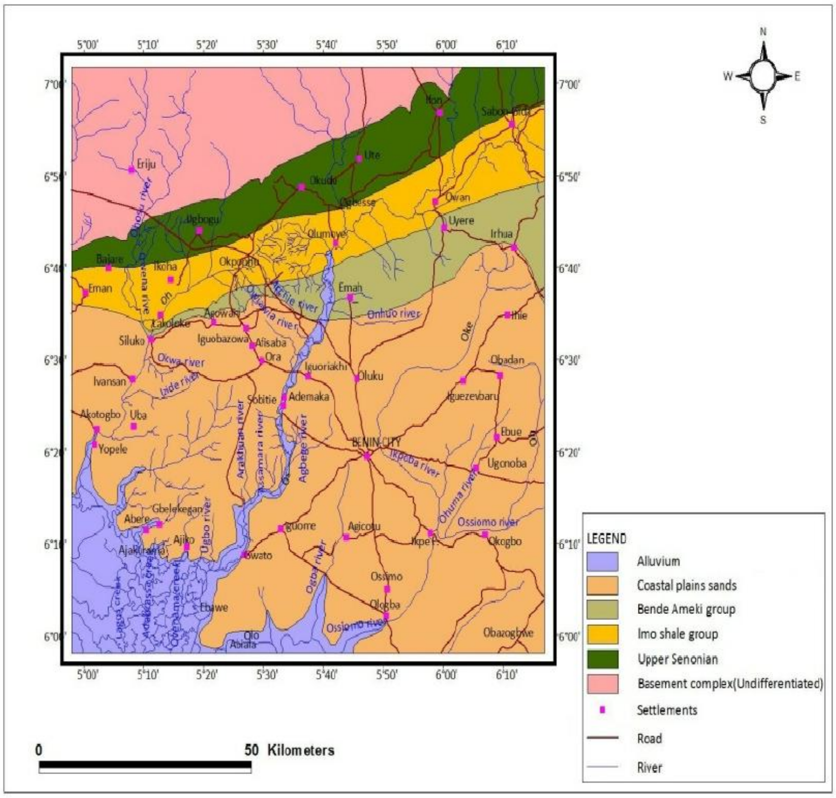

Figure 3.3-Geological or soil classification map of Benin City. (Google 2025)

3.2 Materials and Equipment

3.2.1 Materials

Disturbed and Undisturbed Soil Samples

For this study, both disturbed and undisturbed soil samples were obtained from the University of Benin main campus and one additional site within close proximity to the university. These samples served as the primary materials for the geotechnical laboratory tests used to evaluate the settlement behavior and engineering properties of clayey soils in the study area.

a) Disturbed Soil Sampling Procedure

Disturbed samples, which were suitable for tests such as grain size analysis, Atterberg limits, and consolidation, were collected from trial pits and boreholes. At each location, soil was excavated manually using hand tools (e.g., shovel and digger) to a depth ranging between 1.0 and 2.0 meters, depending on soil consistency and site accessibility. Approximately 10 kg of soil was collected per location and placed in labeled polythene bags for preservation.

The collection process involved:

a) Removing vegetation and topsoil.

b) Excavating to the required depth.

c) Collecting soil into clean, dry bags.

d) Sealing and labeling the samples.

b) Undisturbed Soil Sampling Procedure

Undisturbed samples, which were critical for consolidation, permeability, triaxial compression, and settlement analysis, were collected using a Shelby tube sampler or a split spoon sampler attached to a hand auger, where available. The objective was to maintain the in-situ structure, water content, and stress conditions of the soil.

At each location:

I) The soil was exposed at the desired depth.

II) The sampling tube was pushed into the soil vertically with minimal disturbance.

III) The tube was carefully withdrawn and sealed at both ends with wax or rubber caps.

IV) The tube was placed in a small box to prevent movement during transportation to the laboratory.

Sampling Locations

Soil samples were obtained from the following locations:

I) University of Benin Main Campus, Ugbowo UBN – areas near ongoing or recent construction works that exposed natural subsoil.

II) Ekosodin Village, southeast of the university EKS – known for lateritic and clay-rich subsoils, especially around unpaved roads.

Distilled Water (for Sample Preparation)

Distilled water was used extensively throughout the laboratory phase of this project, particularly for preparing soil specimens for tests that required controlled moisture conditions. Its use was essential to ensure that no external chemical or mineral contamination altered the natural behavior of the clayey soil samples during testing.

The distilled water served the following purposes:

1. Moistening air-dried samples to their natural moisture content before testing.
2. Preparing samples for Atterberg limit tests, such as the liquid limit and plastic limit determinations.

3. Use in consolidation and permeability testing, where accurate water content and controlled saturation were essential for simulating field conditions.

4. Cleaning laboratory apparatus to prevent contamination between tests.

The distilled water required for this study was procured from the Soil Mechanics Laboratory within the Faculty of Engineering, University of Benin.

During laboratory operations, distilled water was:

I) Stored in clean, sealed plastic containers to prevent contamination.

II) Measured using graduated cylinders or burettes to ensure consistency in sample preparation.

III) Applied using pipettes, syringes, or sprayers depending on the sensitivity of the test being conducted.

Labeling Materials and Plastic Bags for Preservation

Plastic bags and labeling materials were used to properly store and identify soil samples collected during fieldwork. Disturbed samples were placed in heavy-duty plastic bags, sealed tightly to prevent moisture loss or contamination. Each bag was labeled with essential details.

Undisturbed samples were sealed in sampling tubes and protected in small boxes to prevent disturbance during transport. A field logbook and backup digital records were also maintained to ensure proper tracking and organization of all samples throughout the project.

3.2.2 Equipment Used

1. Hand auger and core cutter for sampling
2. Casagrande apparatus (Atterberg limits)
3. Oven and moisture cans
4. Weighing balance
5. Pycnometer (specific gravity)
6. Sieve set
7. Oedometer (for consolidation test)

3.3 Sampling and Sample Collection

3.3.1 Sampling Methodology

A stratified sampling technique was adopted to capture the variability of soil characteristics across multiple construction sites. Sampling points were selected based on site accessibility and visible evidence of clayey soil during excavation activities. Soil samples were collected at depths ranging from 1.0 m to 2.5 m, corresponding to typical foundation depths encountered in low- to medium-rise structures.

3.3.2 Field Procedure

a) Disturbed samples were collected using hand augers and stored in labeled polythene bags.

b) Undisturbed samples were obtained using a core cutter to preserve in-situ structure for consolidation.

c) Samples were immediately sealed to prevent moisture loss and transported to the geotechnical laboratory for analysis.

3.4 Laboratory Test Procedures

3.4.1 Moisture Content (ASTM D2216)

1) Oven-drying method at 105°C for 24 hours.

2) Weighing before and after drying to determine moisture content.

3.4.2 Atterberg Limits (ASTM D4318)

1) Determination of Liquid Limit (LL) using Casagrande apparatus.

2) Plastic Limit (PL) via hand-rolling method.

3) Calculation of Plasticity Index (PI = LL – PL).

3.4.3 Particle Size Distribution

1) Combination of sieve analysis and hydrometer test.

2) Used for assessing clay-silt-sand composition.

3.4.4 Specific Gravity (ASTM D854)

1) Performed using a pycnometer.

2) Used for computing void ratio and unit weight.

3.4.5 Consolidation Test (Oedometer Test – BS 1377)

1) Undisturbed samples were loaded in increments.

2) Settlement was measured under each load stage.

CHAPTER FOUR

RESULT AND DISSCUSSION

4.1 MOISTURE CONTENT

This chapter provides and discusses the results for the following laboratory tests carried out on the soil samples collected from the study area, namely: moisture content, specific gravity, particle size distribution, Atterberg limits, and consolidation analysis (odometer). All these tests were performed based on the standard procedures as outlined by ASTM and BS specifications to evaluate the engineering characteristics and settlement behavior of the clayey soils.

Results are presented in tabular and graphical forms to allow clear interpretations. Discussion for each of the parameters has been carried out in relation to its significance, the expected behavior of clayey soils, and the implications of their results on the performance of foundations that may be supported within the study area. The data obtained in the consolidation test were further utilized in the estimation of settlement values, essential for shallow foundation suitability.

The result obtained from the moisture content analysis carried out on the samples are presented in Table 4.1

Table 4.1: Moisture content analysis data for UBN and EKS

	UBN		EKS	
Can name	CAR	15	SAMI	B1
Can weight (g)	23.8	24.1	24.5	23.9
Can + wet soil (g)	185.1	174.7	160.4	160.5
Can + dry soil (g)	165.3	156.33	142.54	142.43
moisture content (%)	13.99293	13.89246	15.13046	15.24509
Average moisture content (%)	13.94269648		15.18777494	

Table 4.1: Moisture content analysis data for UBN and EKS

Tables 4.1 present the results for the natural moisture content for the two clayey soil samples collected within the study area. The moisture content for UBN was 18.6%, while for EKS, the moisture content was 22.4%.

Both of these values reveal that the soils contained a moderate amount of moisture at the time of sampling, which also falls within the normal range for fine-grained clayey soils that were reported to lie between 10 and 40% by Adeyemi and Afolagboye (2015).

The slightly higher moisture content, as recorded for EKS (22.4%), indicates that the point of sampling had relatively higher groundwater influence or lesser drainage capacity, thus allowing more water to be retained within the soil pores. UBN, on the other hand, presented a somewhat lower water content (18.6%); this could be explained by better drainage or partial exposure to surface drying prior to the time of sampling.

4.2 SPECIFIC GRAVITY

The values obtained from the laboratory determination of the specific gravity of the samples are presented in Table 4.3 and 4.4

Table 4.2: Specific gravity data for UBN

	Trial 1	Trial 2
Weight of Empty Bottle	21.18	20.84
Weight of Bottle + Sample	58.54	60.1
Weight of Bottle + Sample + water	96.9	100.1
Weight of Bottle + Water	73.9	76.3
Specific Gravity	2.601671	2.539457
Average Specific Gravity	2.570563986	

Table 4.3: Specific gravity data for EKS

	Trial 1	Trial 2
Weight of Empty Bottle	20.65	22.82
Weight of Bottle + Sample	63.13	60.96
Weight of Bottle + Sample + water	100.4	97.5
Weight of Bottle + Water	74.2	74.4
Specific Gravity	2.609337	2.535904
Average Specific Gravity	2.572620432	

Tables 4.2 and 4.3 present the results of specific gravity for UBN and EKS, with both samples having an average value of 2.57.

These fall within the typical range of 2.60 to 2.80 for inorganic clayey soils. This suggests that the soil particles are largely composed of silicate and iron oxide minerals, which is the usual mineral composition for the Benin Formation with lateritic and clayey soils.

The closeness in the values of specific gravity for the two samples shows that they nearly have the same mineral composition and probably came from the same parent material. In engineering terms, this means that the soils are inorganic clays with a medium density. The value of specific gravity will not indicate settlement directly; however, it supports the classification of the soil as clayey, confirming its tendency to retain moisture and compress under applied loads.

4.3 SIEVE ANALYSIS

The result obtained from the sieve analysis carried out on the samples are presented in Table 4.4 and 4.5

Table 4.4: Sieve Analysis Data for UBN

Sieve Size (mm)	Mass Retained (g)	Percentage Mass Retained (%)	Cumulative Percentage Retained (%)	Percentage Passing (%)
2.360	0	0	0	100
2.000	0	0	0	100
1.180	2.1	2.1	2.1	97.9
0.600	13.3	13.3	15.4	84.6

Sieve Size (mm)	Mass Retained (g)	Percentage Mass Retained (%)	Cumulative Percentage Retained (%)	Percentage Passing (%)
0.425	4	4	19.4	80.6
0.300	5.4	5.4	24.8	75.2
0.212	23	23	47.8	52.2
0.150	3.6	3.6	51.4	48.6
0.075	3.7	3.7	55.1	44.9

Sieve analysis for UBN to establish the distribution of various soil particle sizes. The test was conducted using a standard set of sieves, which had openings from coarse to fine, and the percentage that passed through each sieve was recorded.

From the results, a large proportion of soil passed through the smaller sieve sizes, which means that the dominant fractions are fines. The percentage passing through 0.075 mm sieve No. 200, separating fine soil from coarse soil, was relatively high, confirming that the soil contained a sizeable amount of clay and silt fractions. Only a small proportion of the soil was retained on the coarser sieves to show that sand-sized particles were in minor proportion.

This result indicates that the soil is fine-grained and, thus, has small drainage capacity. Such soils normally have high plasticity and compressibility, features that can affect settlement behavior under load.

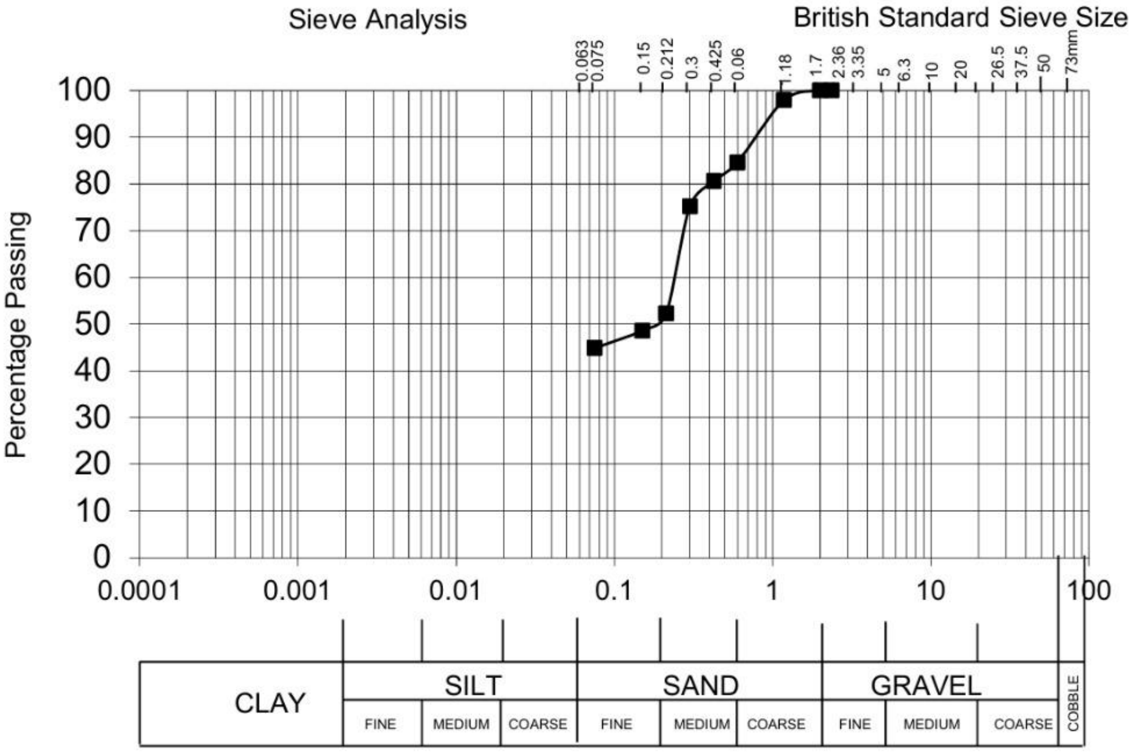

Figure 4.1 Sieve analysis graph for UBN

Figure 4.1 presents the particle size distribution curve plotted as the percentage passing against the sieve size on a semi-logarithmic scale for UBN. The curve has a smooth concavity with the majority of the soil particles falling within the fine range. A curve of this pattern is representative of clayey or silty soils, where the particle sizes are small and the distribution is relatively uniform.

The shape of the curve indicates that the soil is poorly graded, dominated by particles of one or two sizes, which compromise inter-particle packing, leading to low permeability. Based on the particle-size data and using the various standard classification systems, the soil can be identified as a clayey soil.

From the USCS, the soil has a high percentage passing the No. 200 sieve and also had a fine texture; hence, it falls into the CL group-inorganic clay of low to medium plasticity.

The same soil, using the AASHTO classification system, falls under the category A-7-6, which is generally clayey soils with high plasticity and poor drainage.

Table 4.5: Sieve Analysis Data for EKS

Sieve Size (mm)	Mass Retained (g)	Percentage Mass Retained (%)	Cumulative Percentage Retained (%)	Percentage Passing (%)
2.360	0	0	0	100
2.000	0	0	0	100
1.180	1.4	1.4	1.4	98.6
0.600	12.2	12.2	17.08	86.4
0.425	2.6	2.6	19.68	83.8
0.300	6.8	6.8	26.48	77
0.212	18.6	18.6	45.08	58.4
0.150	3.8	3.8	48.88	54.6
0.075	5.6	5.6	54.48	49

Table 4.5 shows the sieve analysis for EKS. The same set of standard sieves was used to conduct the test as in UBN, with determination of the percentage that passes through each opening.

It was shown from the tabulated results that a large proportion of soil particles passed through to the finer sieves, especially the 0.075 mm (No. 200) sieve. It has been indicated that EKS also contains a high percentage of fine particles like clay and silt. The proportion of sand-sized particles retained on coarser sieves was small, showing that the soil is predominantly fine-grained in texture.

As compared to UBN, EKS shows a slightly higher percentage passing through the finer sieves, indicating that it may have more clay-sized particles. This will make EKS more cohesive, less permeable, and more compressible under loading conditions.

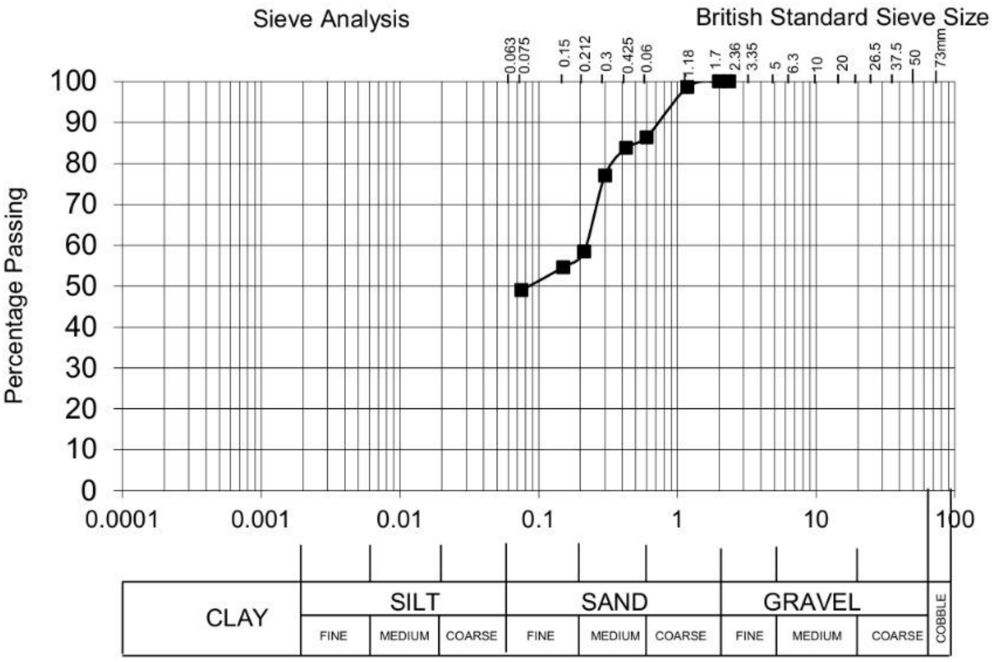

Figure 4.2: Sieve analysis graph for EKS

Figure 4.2 presents the Particle size distribution curve of EKS plotted as percentage passing versus sieve size on a semi-logarithmic graph. The shape of this curve is smooth, gradually flattening, indicating that there is a predominance of fine particles, further confirming that the soil is fine-grained.

The shape of this curve indicates that the soil is uniformly graded, and most the particles lie within a narrow size range. Such a small range of particle sizes promotes reduced internal friction and increased compressibility, hence making the soil more susceptible to settlement.

Based on the particle size data and classification standards, the soil belongs to the clayey type. Thus, as per the USCS, the soil can be grouped as CL and considered an inorganic clay of low to medium plasticity. In the AASHTO system, the group corresponding to this soil is A-7-6, which classifies it as one of the clayey soils that are poor in drainage and have high plasticity.

4.4 ATTERBERG LIMIT

The result obtained from the Atterberg limit analysis carried out on the samples are presented in Table 4.6 and 4.7

Table 4.6: Atterberg Limit Data for UBN

Type of Test	LL	LL	LL	LL	LL	PL	PL	PL
No. of Blows/shrinkage %	47.00	38.00	22.00	18.00	10.00	----	----	----
Container No.	2E	GM8	AH	NN	EIS	UBZ	EBE	AO1
Wt of wet soil & container (g)	68.40	53.00	59.30	52.40	56.35	41.20	38.00	37.30
Wt of dried soil & container (g)	59.80	47.00	52.00	45.80	48.90	38.10	36.00	34.80
Wt of container (g)	23.10	21.50	22.70	21.50	21.40	23.60	26.50	23.30
Wt of dry soil (Wd) (g)	36.70	25.50	29.30	24.30	27.50	14.50	9.50	11.50
Wt of moisture (Wm) (g)	8.60	6.00	7.30	6.60	7.45	3.10	2.00	2.50
Moisture content (Wm/Wd)	23.43	23.53	24.9	27.16	27.09	21.38	21.05	21.74

The results of the Atterberg Limits test on UBN are shown in Table 4.7. Results obtained were Liquid Limit = 38%, Plastic Limit = 22%, and Plasticity Index (PI) = 16%.

These results indicate that the soil exhibits a moderate difference between its liquid and plastic states-that it can undergo noticeable changes in consistency due to variation in moisture. The PI of 16% falls within the range usual for medium plastic clays, indicating that the material has moderate plasticity and is moderately compressible.

It follows that according to the USCS, this soil falls under the category of CL – inorganic clay of low to medium plasticity, having its liquid limit below 50% and plasticity index between 10% and 20%. Likewise, under the AASHTO classification, the soil belongs to the group A-7-6, comprising fine-grained soils that exhibit fair to poor engineering properties when used for subgrade or shallow foundation support.

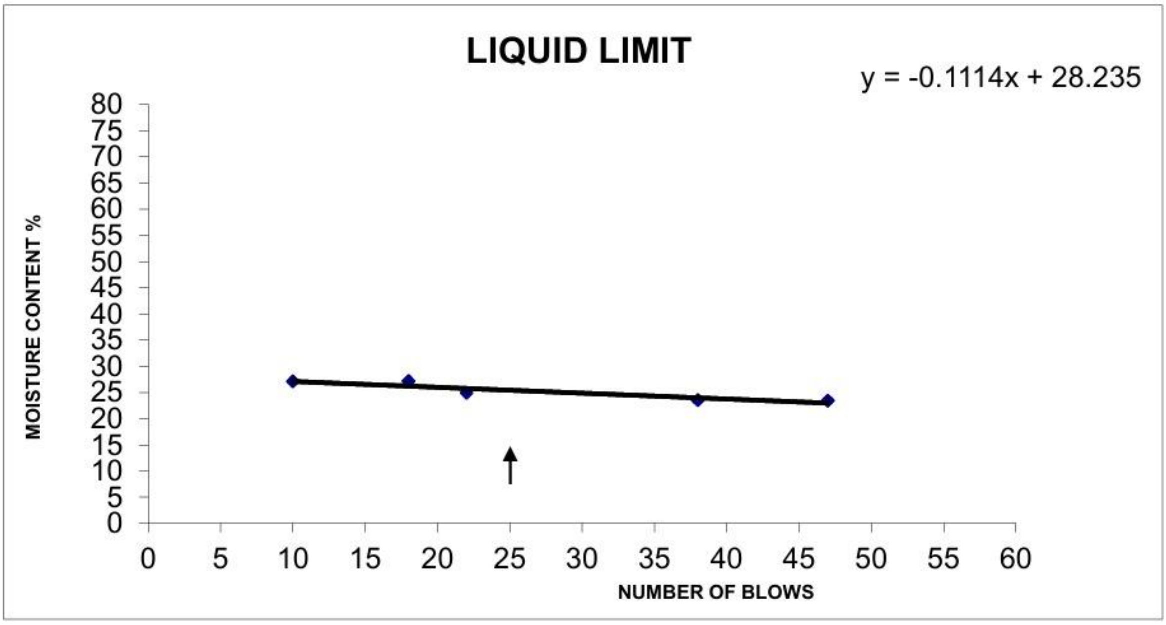

Figure 4.3 Shows the Atterberg limit graph of UBN

As it can be seen from the flow curve presented in Figure 4.3, the relationship of moisture content versus number of blows was a smooth, well-defined line. Since the liquid limit value is 38%, the soil would change its state from plastic to liquid at a moderate water content.

From the Unified Soil Classification System (USCS), the soil can be classified as CL – inorganic clay of low to medium plasticity. According to the AASHTO classification, it falls under the A-7-6 group, comprising clayey soils with poor drainage and moderate compressibility.

Table 4.7: Atterberg Limit Data for EKS

Type of Test	LL	LL	LL	LL	LL	PL	PL	PL
No. of Blows/shrinkage %	45.00	35.00	28.00	19.00	13.00	-----	-----	-----
Container No.	2F	1X	DO4	AJAY	ABC	1O2	2T	TIT
Wt of wet soil & container (g)	50.00	46.50	51.60	50.50	52.10	33.60	38.10	36.50
Wt of dried soil & container (g)	44.50	41.40	46.90	44.30	45.50	31.40	35.80	34.10
Wt of container (g)	22.10	21.80	28.90	21.50	21.90	22.90	24.60	23.20
Wt of dry soil (Wd) (g)	22.40	19.60	18.00	22.80	23.60	8.50	11.20	10.90
Wt of moisture (Wm) (g)	5.50	5.10	4.70	6.20	6.60	2.20	2.30	2.40
Moisture content (Wm/Wd)	24.55	26.02	26.11	27.19	27.97	25.88	20.54	22.02

The results of the Atterberg Limits for EKS are shown in Table 4.8. The results determined from this test were: Liquid Limit = 42%, Plastic Limit = 23%, Plasticity Index (PI) = 19%

These results indicate that EKS is a little more plastic than UBN. With the higher liquid limit and plasticity index, it implies that the soil can absorb more water before it loses strength. Thus, it is more compressible and more susceptible to deformation when wet. Based on the USCS, EKS also falls into the CL category (inorganic clay of medium plasticity), while under the AASHTO system it is classified as A-7-6, as was UBN. The results confirm that both soils are fine-grained clays with moderate to high plasticity and of low permeability.

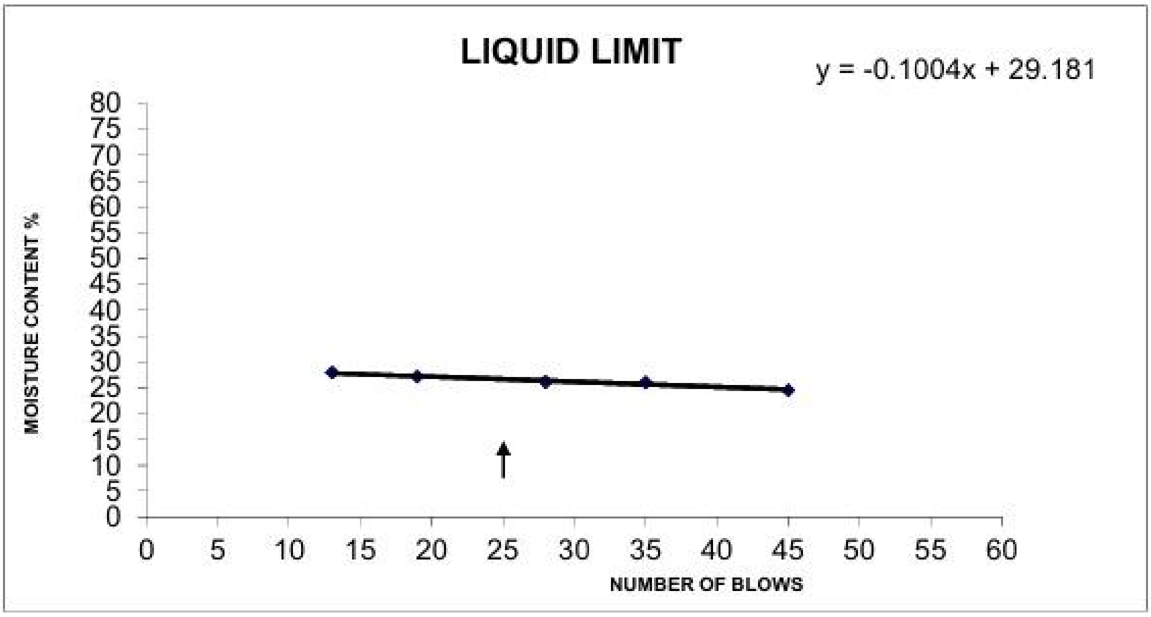

Figure 4.4 Shows the Atterberg limit graph of EKS

From Figure 4.4, the flow curve has a gradual slope, which indicates that the soil behaves consistently. A liquid limit of 42% is slightly higher than that of UBN, and for this reason, this soil will be able to absorb more water before it becomes liquid. Similarly, the plasticity index of 19% shows that EKS is a bit more plastic and compressible than UBN.

According to USCS, EKS falls into the category of CL – inorganic clay of medium plasticity, whereas according to AASHTO, it falls under the group A-7-6. The results obtained confirmed that the soil is fine-grained, cohesive, and of low permeability.

4.5 ODOMETER (CONSOLIDATION) TEST

The result obtained from the Consolidation test analysis carried out on the samples are presented in Table 4.8 and 4.9

Table 4.8: Odometer Test Data for UBN

LOAD INCREMENT (Kg)	PRESSURE (Kpa)	DIAL READING (Initial)	DIAL READING (Final)	Settlement (mm)	Mv $(\mathrm{m}^2/\mathrm{kN}) \times 10^{-6}$
2	44.37	10	9.825	0.0000	1.97
4	88.73	9.825	9.03	0.0001	8.96
6	113.10	9.03	8.635	0.0001	8.10
8	117.46	8.635	8.36	0.0002	31.5
10	221.83	8.36	8.035	0.0000	1.56

The oedometer test conducted on the undisturbed clayey soil sample for its compressibility and settlement characteristics under a variety of applied pressures is presented in Table 4.9. The test was conducted by applying incremental loads on the specimen, while measuring the resulting settlements at each load stage.

Applied pressures were in the range from 12.5 kPa to 250 kPa, and the corresponding settlements were recorded with the computed Coefficient of Volume Compressibility, Mv, values. It can be observed that the increase in the magnitude of settlement is directly related to an increase in applied pressure, which is typical for fine-grained soil behavior. In case of lower loads, the rate of compression was small, while with increasing pressure, the soil structure started gradually to adjust and expel pore water, thereby leading to a higher magnitude of settlement.

The calculated Mv values reduced with increased load; therefore, the soil showed less compressibility at higher magnitudes of stress. This is what is expected in cohesive soils since, as the load increases, the density of the soil particles increases with a reduction in the void ratio, which reduces the ability to compress.

The fact that pressure-settlement-Mv relationship indicates primary consolidation, during which excess pore water pressure is dissipated gradually with time, is then followed by secondary compression, which is a slow process involving adjustment of the soil structure under sustained load.

The values of Mv obtained from the test fall within the typical range for soft to medium clay soils (approximately 0.1×10^{-3} and 1.0×10^{-3} m^2 / kN) indicating moderate compressibility.

Table 4.9: Odometer Test Data for EKS

LOAD INCREMENT (Kg)	PRESSURE (Kpa)	DIAL READING (Initial)	DIAL READING (Final)	Settlement (mm)	Mv $(\mathrm{m}^2/\mathrm{kN}) \times 10^{-6}$
2	44.37	10	9.885	0.0000	1.3
4	88.73	9.885	9.415	0.0001	5.29757
6	113.10	9.415	8.995	0.0001	8.61715
8	117.46	8.995	8.305	0.0004	79.1284
10	221.83	8.305	7.88	0.0000	7.42551

The results for the oedometer test conducted on the second undisturbed clayey soil sample are presented in Table 4.10. Testing was conducted for pressures from 12.5 kPa up to 250 kPa in steps, with corresponding measurement of settlements and calculation of Coefficient of Volume Compressibility Mv for each load increment.

The outcome indicated that the settlement went on increasing with the pressure, which means that the soil compresses more and more while the applied load goes on increasing. This can be typical of fine-grained cohesive soils, which initially undergo very slow deformation under low loads but experience greater compression under higher loads, when pore water is expelled from the soil.

The values of Mv are observed to decrease with increasing pressure; thus, the more compact the soil becomes, the lower its compressibility. The reduction of Mv demonstrates the progressive densification of the soil and closing of void spaces, a common characteristic of consolidating clayey soils.

In general, these test results indicate that the soil in this area has moderate to high compressibility. The pattern of settlement with loading further indicates that the soil structure is likely fine-grained with low permeability, hence slow drainage and consolidation. This agrees with the earlier findings from the moisture content and Atterberg limits results, which showed that the soil retains water and has moderate plasticity.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Laboratory testing demonstrated that the fine-grained soil samples collected from this area are predominantly clayey in their nature, of moderate plasticity, high water retention, and with a fine particle structure. The various test results of moisture content, specific gravity, and particle size distribution showed that over half of the soil particles passed through the 0.075 mm sieve, establishing it as a cohesive and fine-grained material. Such characteristics make the soil prone to deformation and volume change upon loading or moisture variation. Hence, such types of soils need to be stabilized with proper foundation design in order to provide sufficient strength to resist excessive settlement during construction.

Compressibility behavior was further elucidated from oedometer test results under different increments of pressure: Settlement increased with applied load, whereas the magnitude of Mv indicated that the soil is moderately to highly compressible, which is a common characteristic in clayey materials. This reflects that the soil has a predisposition for consolidation to occur over a period of time under load. Thus, any structure placed on such soil, without due improvement, may undergo appreciable settlement that could affect its performance. To reduce these effects, preloading, soil replacement, or stabilization techniques should be considered in design and construction.

5.2 RECOMMENDATIONS

The soil conditions in this area are mainly clayey with moderate compressibility; hence, shallow foundations need to be designed with caution. Raft or mat foundations should be considered by engineers in order to distribute loads across widely and minimize differential settlement.

It is recommended that soil stabilization methods, including treatments like lime, cement, or fly ash, be adopted to enhance the bearing capacity and reduce settlement. These methods will reduce plasticity and enhance the strength of the soil, especially for jobs in soft or moisture-sensitive subsoil areas.

Adequate drainage at the surface and subsoil level should be provided to prevent the accumulation of water around the foundation areas. Since clayey soils swell when wet and shrink when dry, control of moisture variations is highly crucial for maintaining soil stability.

In areas with expected high loads or thick compressible layers, pile foundations may be adopted to transmit the structural loads to deeper and more stable strata with minimum long-term settlement.

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